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DEFENSE METEOROLOGICAL SATELLITE PROGRAM - SPECIAL SENSOR J5 (SSJ5) SENSOR NUMBER 16 (SN16) CALIBRATION REPORT

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Technical Report

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14. ABSTRACT

The Defense Meteorological Satellite Program (DMSP) Special Sensor J5 (SSJ5) Serial Number 16 (SN16) was the SSJ5 protoflight model, however it was flown on DMSP F16. A SSJ5 is a charged particle analyzer, which uses an electrostatic deflection system to sort and analyze ions and electrons encountered in low earth orbit polar flight paths. Prior to launch, controlled electron and ion beams are used in the laboratory to measure the instrument's dynamic response, to verify performance, and to determine coefficients required to convert raw orbital count rates into engineering units allowing for the calculation of the geophysical quantities of differential number flux and differential energy flux. Included in the pre-delivery testing were several electron and ion calibration runs conducted to verify performance, determine the geometric factors (g-factors) and $\Delta E/E$ at a variety of energies, and check count rate linearity. This report chronicles the events and calibrations of SSJ5 SN16 and presents the results of those efforts.

15. SUBJECT TERMS
Charged Particle Analyzer, SSJ5, SN16, Defense Meteorological Satellite Program, calibration, geometric factors, DMSP F16, Microchannel Plates

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1. INTRODUCTION

Special Sensor J5s (SSJ5s), charged particle analyzers, are flown on the Air Force Defense Meteorological Satellite Program (DMSP) satellites. These sensors were manufactured by Amptek, Inc., located in Bedford MA. The SSJ5s uses an electrostatic deflection system to sort and analyze ions and electrons encountered in low earth orbit polar flight paths. The SSJ5 has a mass of 3.2 kg, nominal power of 1.4 W, and a size of 23 x 15 x 15 cm^3. The SSJ5s consist of two 270^o triquadraspherical electrostatic analyzers each backed by a single arc-segmented microchannel plate (MCPs) with a 90° x 4° field of view. The 90° zenith to horizon dimension is divided into six 15° angular sectors. Electron and ion counts at 19 energies, from 30eV to 30 keV, are measured each second, with a normal dwell time of 50 msec per energy channel.

There were five SSJ5s built for the DMSP satellites by Amptek Inc. delivered between 1993 and 1997 [1]. Listed in Table 1 are all the SSJ5s and the DSMP spacecraft that they were manifested on. Prior to launch the DMSP spacecraft is referred to by its serial number (example, S20) and after launched it is its flight number (example, F16).

Table 1. History of the SSJ5s built for DSMP [1]

SSJ5 Serial Number	DMSP Spacecraft Number	Initial Delivery Date	Date Return to AFRL	Final Delivery	Launch Date
SN16	S20 (F16)	28 Oct 1993	14 Mar 2001	8 Jul 2002	18 Oct 2003
SN17	S19 (F18)	17 Apr 1995	22 Jan 2003	26 Mar 2009	18 Oct 2009
SN18	S16 (F20)	Feb-Apr 1996	19 Feb 2010	01 May 2013	——
SN19	S18 (F19)	Sept 1996	Apr 2005	20 Feb 2013	3 Apr 2014
SN20	S17 (F17)	21 Apr 1997	20 Jan 1999	03 Dec 2004	4 Nov 2006

Reported here are the ground-calibrations and associated activates of the DSMP SSJ5 SN16 that were conducted prior to launch. However, over the intervening years since the launch of the SSJ5 SN16 there have been recalculations of the necessary calibration coefficients from the calibration data, which was based on to insights gained from all the calibration and flight history of the SSJ5s. For current calibration coefficients, i.e. geometric factors, channel central energy and channel spacing, for the SSJ5 SN16 (launched on DMSP S20 (F16)) refer to AFRL Technical Report AFRL-RV-PS-TR-2014-0174 [2].

Prior to launch, controlled electron and ion beams are used in the laboratory to measure the instrument's dynamic response, to verify performance, and to determine coefficients required to convert raw orbital count rates into engineering units of flux [3]. Sensors counts are converted to physical quantities of differential number flux (J_i) and differential energy flux (JE_i) given as:

$$J_i = C_i / (GF_i * \Delta t) \quad cm^{-2}s^{-1}sr^{-1}eV^{-1}, \tag{1}$$

$$JE_i = J_i * E_i \quad cm^{-2}s^{-1}sr^{-1}, \tag{2}$$

where C_i is the number particle counts measured in channel i; Δt the preset dwell time (0.05 seconds); GF_i is the appropriate ion or electron channel geometric factor determined during the laboratory calibration; and E_i is the channel central energy. The integrated number flux (J) and integrated energy flux (JE) is given as:

$$J = \sum_i J_i \, \Delta E_i \quad cm^{-2}s^{-1}sr^{-1}, \tag{3}$$

$$JE = \sum_i JE_i \, \Delta E_i \quad cm^{-2}s^{-1}sr^{-1}eV, \tag{4}$$

where the summation is over the full energy range of the sensor (30 eV to 30 keV)and ΔE_i is the channel energy spacing for calculating the integrated quantities. This ΔE_i should not be confused with the measured channel energy width of the sensor which depends on the sensor geometry. The measured channel energy width, $\Delta\mathcal{E}$, is only used to calculate the sensor's geometric factor and is reported in this paper. The ΔE_i used for the calculation of J and JE can be found in Ober *et. al.*[2].

The SSJ5 SN16 sensor was the SSJ5 protoflight model. It was delivered 28 October 1993 to the DMSP spacecraft integrator Martin Marietta Astro Space (MMAS) in Princeton, NJ, after extensive testing (EMI / EMC tests, OLS compatibility tests, two protoflight level vibration tests, thermal and thermal vacuum tests, acceptance level vibration test, and final electrical tests). Included in the pre-delivery testing were several electron and ion calibration runs conducted to verify performance, determine geometric factors and $\Delta\mathcal{E}/E$ at a variety of energies, and check count rate linearity (hereafter referred to as the 1993 calibration).

The SSJ5s used microchannel plates (MCPs) as the particle sensing element and it was known that the efficiency decreased with storage time, thus it was planned to return the SSJ5 units prior to launch and replace the MCPs and then preform the final ground calibration. MPC efficiency is known to degrade with exposure to the atmosphere. The MPCs used in the SSJ5s were of a newer design than those reported in the scientific literature and were expected to be more tolerant of atmospheric conditions than previous manufactured MCPs. It was judged that the replacement cost was more economic than the risk of a flying a set of MCPs with a shortened life expectancy. Because the replacement of the microchannel plates required re-calibration, the geometric factors derived in the 1993 calibration work were only intended to demonstrate instrument integrity and verify the design and manufacturing process.

1.1 Refurbishment of SSJ5 SN16

On March 14, 2001, the SSJ5 SN16 sensor was retrieved from Lockheed Martin Space Systems Company, Sunnyvale, CA, and returned to AFRL, Hanscom AFB, MA. The sensor was to be used as the spare for DMSP S20 (F16), because at that time there was a concern that the recently refurbished and calibrated SSJ5 SN20 flight unit had been exposed to a contaminant at the launch pad. The SSJ5 SN16 sensor remained at AFRL, Hanscom AFB, MA, while SSJ5 SN20 was examined and re-delivered to Lockheed Martin Space Systems Company, Sunnyvale, CA. Refurbishment of SSJ5 SN16 began in June 2001. Prior to refurbishment, a short calibration was conducted in May-June 2001, which verified its liveness and sensitivity of the instrument with its original microchannel plates after 8 years of storage under atmospheric conditions. During the

period June-August 2001, the instrument was refurbished. The refurbishment included the following items:

1. Replacement of power supply transformers. The original transformers used an elastic silicone potting compound, and Amptek had discovered on another program that moving the transformer leads could trap a small amount of gas that could ionize over time in a vacuum and become a noise source. They selected a more rigid compound and replaced the transformers (same transformer type).
2. Removal of outer screen and replacement of apertures for electrons and ions with apertures of increased diameter. These changes were made to enhance the geometric factors for the sensor so that these would more closely match those of its predecessor, the SSJ4 sensors. Old apertures that were removed had diameter for electrons of 0.14 cm and ions of 0.37 cm. The new apertures changed the diameter for the electrons to 0.36 cm and ions to 0.56 cm.
3. Replacement of microchannel plates.

1.2 Calibration of SSJ5 SN16

The calibration of SSJ5 SN16 was comprised of scans that covered for six of the nineteen energy channels, plus ‘mini-scans’ for eighteen (all but the highest energy) channels across all angles in both the azimuth and zenith angles. This was done for both electrons and ions. The result of an energy and angle scan was a four dimensional array of count rates verses azimuth angle, elevation angle, and energy for each of the six directional zones.

Calibration work on SSJ5 SN16 was initiated at AFRL facility at Hanscom AFB, MA in September 2001 after installation of new microchannel plates by Amptex Inc. During this calibration effort cross-talk between angular zones was discovered. The cause of the cross-talk was traced to a higher gain for the new microchannel plates. The cross-talk was successfully eliminated by changing threshold resistors, associated with each preamplifier, to match the new microchannel plate gain. Full calibration for electrons and ions was completed by mid-November 2001 after this adjustment.

In November 2001, the SSJ5 SN16 sensor went through cleaning and staking, received a new flight programmable read-only memory (PROM), and underwent an acceptance level vibration test. In late November 2001, watchdog timer resets were observed during thermal vacuum testing. Testing was halted, and two separate problems were diagnosed. The first problem was a result of the recent vibration test, which had caused one of the leads of a crystal oscillator to crack. The second problem was, related to the use of a new PROM burner, which had introduced an error in the PROM. In January-February 2002 the crystal oscillator and the PROM were replaced, the CPU board underwent an acceptance level vibration test, the sensor went through a thermal vacuum cycle, and a calibration recheck was conducted with no further issues.

1.3 Delivery of SSJ5 SN16 for Integration on DSMP S20 (F16)

After final electrical tests in April 2002, the SSJ5 SN16 sensor remained in storage at AFRL facility at Hanscom AFB, MA. On June 27, 2002 it was delivered to Northrop Grumman Baltimore, MD for cross-country transportation to Vandenberg AFB. It was delivered to

Lockheed Martin at Vandenberg AFB in July 2002 to replace SSJ5 SN20 on DMSP S20 (F16). It had been discovered that the SSJ5 SN20 had the same cross-talk issues as SSJ5 SN16 and it was decided to exchange the SSJ5 SN16 for the SSJ5 SN20 sensor on the DMSP S20 (F16).

From mid-April to mid-October 2002, the SSJ5 SN16 sensor was stored in a clean controlled environment, but it was realized at a later time that the nitrogen purge had not been properly hooked up to the SSJ5 storage box at AFRL from April to June 2002. After some dialog with Lockheed Martin, a nitrogen gas purge line was attached to the sensor on October 17, 2002, while mounted on the spacecraft, to protect the microchannel plates from further degradation while awaiting launch of DMSP S20 (F16). DMSP S20 (F16) was successfully launched on October 18, 2003.

2. BACKGROUND

2.1. Functional description

The SSJ5 instrument consists of a pair of nested triquadraspherical (270°) electrostatic analyzers coupled to a MCP. It was designed to provide data on the characteristics of precipitating auroral particles, which are a major source of energy for the ionosphere. AFRL had previously used triquadraspherical electrostatic analyzers in the Combined Release and Radiation Effects Satellite (CRRES) low energy plasma analyzer [4] and in the Tethered Satellite System (TSS-1) Shuttle Potential and Return Electron Experiment (SPREE) [5].

The use of the hemispherical analyzer to perform energy analysis produces a detector response where the energy range measured is relatively independent of the incident angle. This in turn provides a more accurate determination of the particle flux. The SSJ5 uses its 270° spherical deflection system to discriminate 30 eV through 30 keV ions and electrons. The MCP is then used to amplify and transform single ion or electron events into charge pulses that are counted. The SSJ5 uses the spacecraft bus voltage of 28 volts DC and the data interface to time and transfer energy/count rate results.

Once per second, the SSJ5 measures electrons and ions over an energy range from 30 eV to 30 keV in nineteen logarithmically spaced steps. The field of view is a 4º by 90º fan for electrons and ions ranging from zenith to the horizon. The 90º field of view is divided into six 15º zones or sectors as shown in Figure 1. The SSJ5 has the capability of providing particle pitch angle measurements through the comparison of the six zones once per second.

DMSP required the SSJ5 to continue providing the established functionality of its predecessor, the SSJ4. The main function of the SSJ4, and now the SSJ5, was to identify the auroral boundary crossings of the DMSP satellite. In contrast with the SSJ5, the SSJ4 had cylindrical electrostatic analyzers, a much smaller zenith-oriented field of view, and did not provide the arrival angle that could then be converted into pitch angle [6].

The SSJ5 inherited the restricted-bandwidth telemetry of the SSJ4. This telemetry in turn restricts the amount of SSJ5 data that can be retrieved from the DMSP spacecraft (one sixth of the data actually generated by the SSJ5 instrument). The SSJ5 CPU acquires sensor data from the

accumulators and log-compresses the counts in a format that is compatible with the SSJ4. The spacecraft then telemeters the data and instrument status information to the ground.

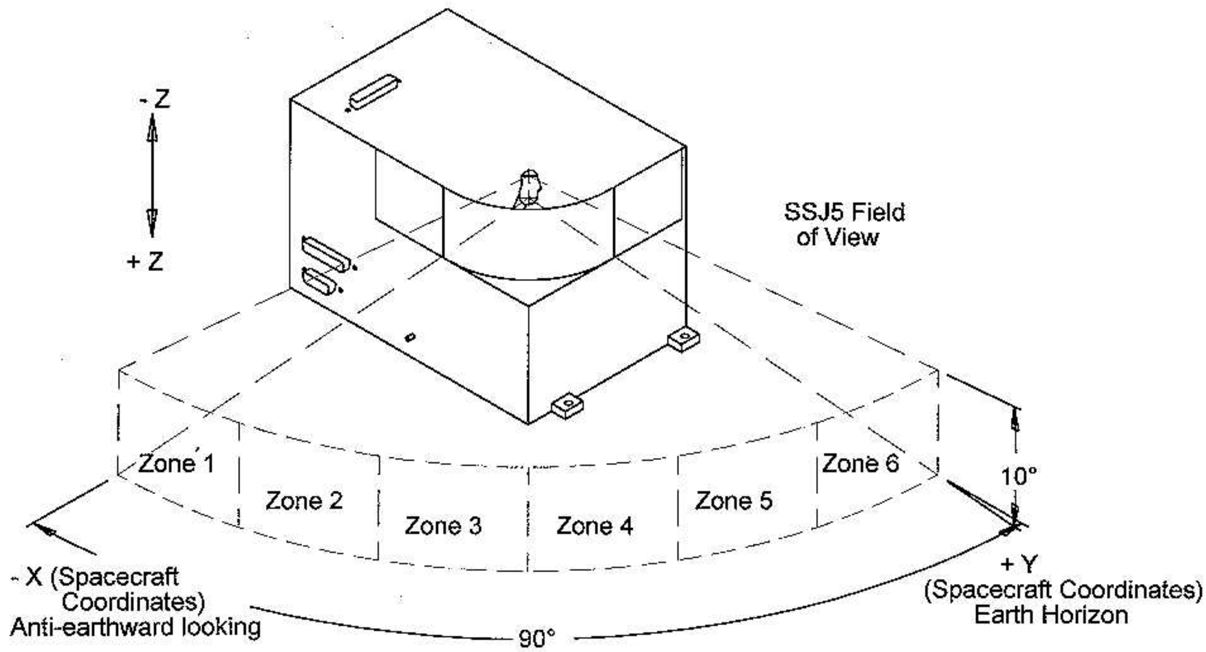

Figure 1. SSJ5 field of view and zones

The SSJ5 can be run in either of two modes, Mode A and Mode B. Each mode has a different format, Format A for Mode A and Format B for Mode B. In Format A, particle counts from all six angular sectors are summed once per second. This emulates the temporal resolution of the SSJ4, which did not have angular zones. In Format B, particle counts from the six angular sectors are provided one zone at a time providing enhanced pitch-angle resolution. Also in Format B, the particle counts for each zone have been summed over the previous six seconds, however the six-second (roughly 40 km) resolution of mode B is less than the inherent one-second resolution of the SSJ5. In addition the six zones are not sampled simultaneously. Both of these limitations of mode B are a result of the spacecraft restrictive telemetry allocation for the SSJ5s. The SSJ5 has been run for extended time periods in both Modes producing Format A and B data. While Format B has reduced precision for determining features such as auroral boundary crossings, it is useful for characterizing the degree of anisotropy of the particle fluxes.

The normal data rate is 1 full energy sweep per second (50 msec accumulation time for each of the 19 energy steps, and a 50 msec flyback interval) that is summarized into 360 bits per second. These 360 bits are divided into forty 9-bit words; 19 logarithmically spaced energy measurements for electrons and ions, and two 9-bit words used for status. Each data word is log compressed using a four-bit exponent and a five-bit mantissa. This scheme allows count rates from zero to 2,064,351 to be contained in 9 bits.

2.2. Simplified Computational Model for SSJ5 Response

A simplified theoretical model of the SSJ5 has been developed by Amptek Inc. that allows reasonable estimates of the analyzer response. Each set of spheres has an inside and outside radius to which the incoming particle fluxes is constrained, where the outer radius is denoted as R_o and inner radius as R_i as shown in Figure 2. Also the diameter of the aperture is denoted as A_p.

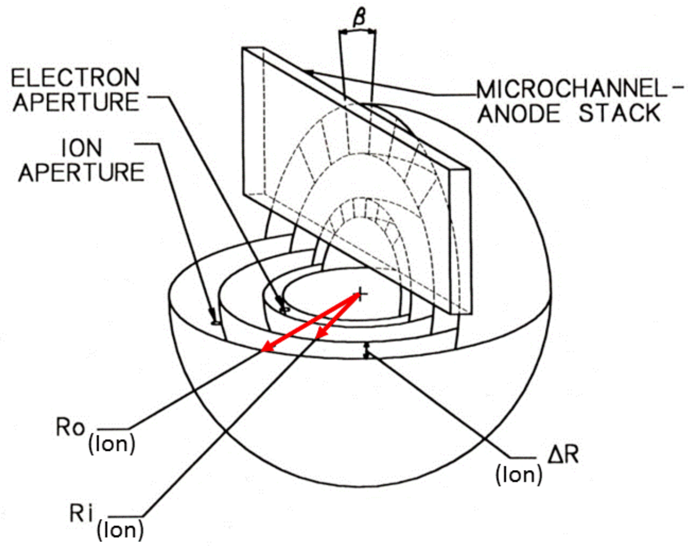

Figure 2. SSJ5 nested triquadrispheres with R_o, R_i and ΔR shown for the ion spheres

These radii combined with the shape and size of the inlet aperture and outlet collection surface determine the sensor response based on the geometry of the sensor. These quantities are used to calculate the following:

1. Delta R = $\Delta R = R_o - R_i$
2. $R_{bar} = (R_o+R_i) / 2$
3. Analyzer Constant = $k = R_{bar} / \Delta R$
4. Energy Bandwidth = $\Delta E / E = \Delta R / 2R_{bar}$
5. α – the focused angle; radial electric field of the deflection plates operates on the charged particle between the plates to select particle polarity and energy.
6. $\alpha = \tan^{-1} ((\Delta R + A_p) / \pi R_{bar})$ as measured at the FWHM point.
7. β – the unfocussed angle; determined by the anode geometry and the aperture dimensions mapped onto anode structure. For the SSJ5 $\beta = 15°$ or 0.261799 radians.
8. The transfer function that translates raw count rates into fluxes is referred to as the energy dependent geometric factor [GF(E)] given as:

$$GF(E) = (A_p^2\ \pi)/4)\ \alpha\ \beta\ C\ \text{cm}^2\text{-steradians.}$$

C is a parameter constant that includes any screen transmissibility that the particle flux may need to navigate and the open area ratio (OAR) of the multiplier plus any known efficiency term. Also

to be considered is cosine dependence of the aperture area at high incidence angles. The geometric factor of the analyzer is maximize while retaining high energy-resolution. It is assumed for this simple model that the MCPs are operating at when calculating the energy dependent geometric factor.

2.3. Specific SSJ5 SN16 Constants

The relevant details for the SSJ5 SN16 instrument are tabulated in Table 2 and the derived characteristics are given in Table 3 with the assumption that the MPCs are operating at 100% efficiency.

Table 2. SSJ5 SN16 measured constants

Species	R_o (cm)	R_i (cm)	ΔR (cm)	R_{bar} (cm)	Ap Dia (cm)	Inner Screen	MCP OAR
Ions	5.461	4.902	0.559	5.182	0.559	83%	55%
Electrons	3.571	3.207	0.364	3.389	0.364	83%	55%

Table 3. SSJ5 SN16 derived constants

Derived Constants	Ions	Electrons
Analyzer Constant	$k = 5.182/0.559 = 9.27$	$k = 3.389/0.364 = 9.31$
Energy Bandwidth	$\Delta E / E = 0.559/(2*5.182) = 5.4\%$	$\Delta E / E = 0.364/(2*3.389) = 5.4\%$
Focused Angle	$\alpha = \tan^{-1}(0.068) = 3.9° = 0.068$ radians	$\alpha = \tan^{-1}(0.068) = 3.9° = 0.068$ radians
Geometric Factor (single sector)	$GF(E) = ((0.559)^2 * \pi/4) * 0.068*0.262 *0.83*0.55 = 2.00 \times 10^{-3}\ cm^2\text{-}sr$	$GF(E) = ((0.364)^2 * \pi/4) * 0.068*0.262*0.83*0.55 = 8.46 \times 10^{-4}\ cm^2\text{-}sr$

3. METHODS, ASSUMPTIONS, AND PROCEDURES

The AFRL calibration facility includes two vacuum chambers (Mumbo and Jumbo) [3, 7], a 10 eV - 50 keV electron source and a 20 eV - 20 keV ion source. The SSJ5 SN16 was calibrated in Mumbo, a 2.4 m long cylindrical stainless steel chamber with a 1.2 m diameter, equipped with cryopump, thermal vacuum capability, Helmholtz coils to null the local earth's magnetic field, a 2-axis gimbal fixture to rotate the device under test in azimuth and elevation, a variety of gauges, and an automated system to control the gimbal system and the particle beam energy and accumulate calibration data. Typical pressures in Mumbo are $10^{-7} – 10^{-6}$ Torr.

The electron source was provided by a 254 nm wavelength Hg lamp located outside the chamber. It illuminated the back of a 0.3 m diameter quartz plate coated with a 40 nm gold film that was located inside the chamber. Photoelectrons are ejected from plate and then accelerated towards

the device under test by an electric field with flux 2 x 10^{-10} mA/cm^2. The ion source was located in an auxiliary chamber that was attached to the end of the Mumbo vacuum chamber. The auxiliary chamber was pumped down using a pair of turbo pumps. A hot filament ionizes a gas at 10^{-5} Torr, typically N_2, and the ions are accelerated down a 1.8 m long differentially pumped drift tube before entering the chamber.

The 2-axis gimbal fixture allows for the rotation of the SSJ5 to line up with the beam of particles in the chamber. The gimbal fixture consists of a pair of rotary tables, one mounted upon the other as shown in Figure 3. The instrument was mounted on the fixture such that the electron/ion apertures are approximately centered at the intersection of the two rotation planes (azimuth and elevation). The dependence of the elevation system on the azimuthal system results in an error in the elevation angle. This error was corrected for during data processing.

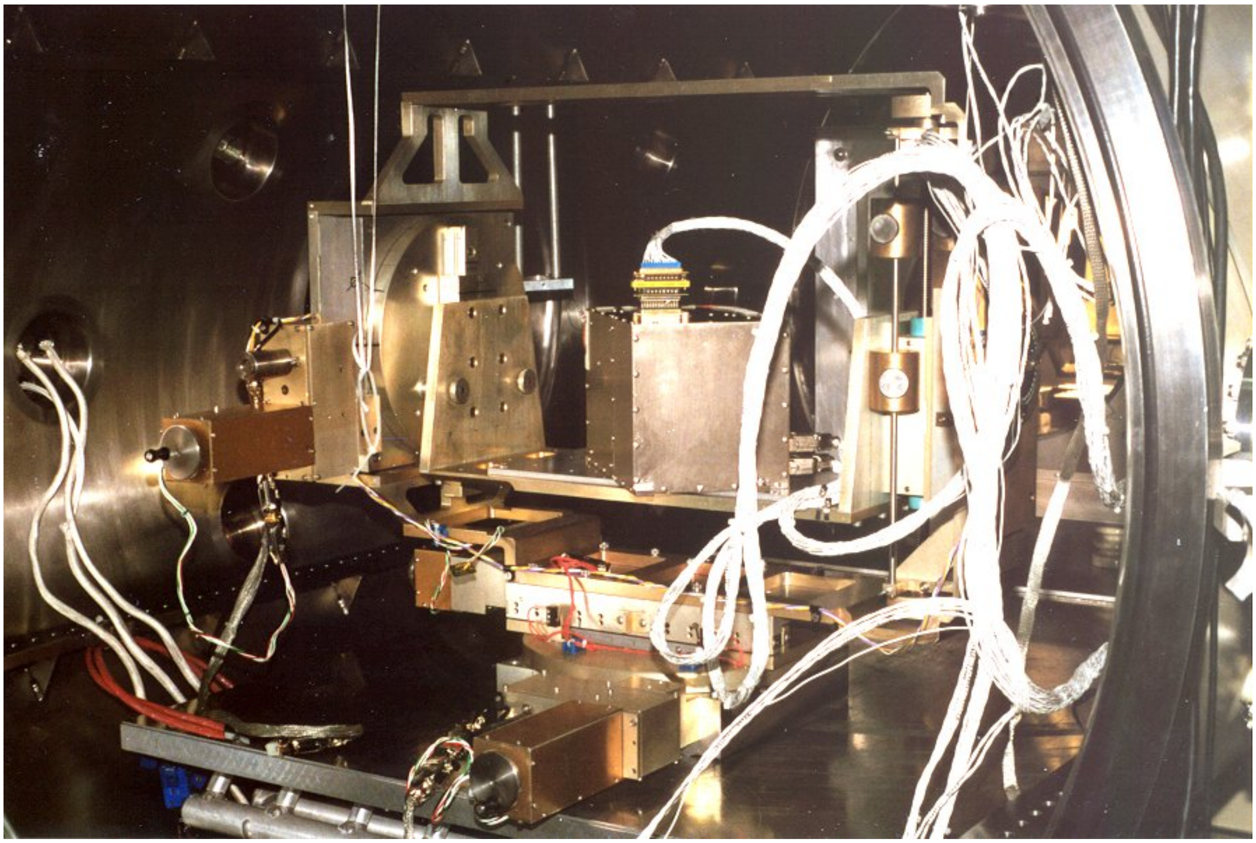

Figure 3. SSJ5 SN16 installed in the Mumbo vacuum chamber at AFRL Hanscom AFB, MA

AFRL's Calsys3 calibration software was used to collect and record SSJ5 SN16 data. Commands were sent to the SSJ5 using the ground support equipment (GSE) computer manufactured by Amptek. The GSE was also used to monitor sensor health in the Equipment Status Telemetry (EST).

Normally the SSJ5 would step through the entire energy range by sampling each of the 19 energy channels, but during a calibration run the sensor is stopped at a given energy channel. Count rates for each to the 6 electron zones and 6 ion zones are recorded. This is repeated until all

energy channels of interest are sampled with source energies in a window centered on the energy step of interest. This process was then repeated as the sensor was reoriented in azimuth and elevation. Independent information about the source particle flux was collected using an electrometer. During the calibration, particle-counting "Amptektrons" sensors, positioned in the chamber, provided independent confirmation of beam and test environment health. Beam-mapping using Amptektrons mounted on an X-Y table provided confirmation that the beam was uniform and directed towards the device under test. If no problems occurred, a calibration run corresponding to one energy step typically took 2 hours for set-up and warm-up, 5-8 hours to accomplish, and half an hour to shut down. Calibration work was not attempted until the instrument had been sitting in the chamber under high vacuum conditions for more than 24 hours; therefore any required experimental adjustments (e.g., cryopump maintenance or wire harness troubleshooting) were likely to generate substantial delays.

3.1 Calibration of SSJ5 SN16, May-September 2001

In May 2001, SSJ5 SN16 was calibrated at AFRL Hanscom AFB, MA, in order to gather data on the suspected microchannel plate deterioration that could have possibly occurred during the 8-year period following the October 1993 instrument delivery. During that period the instrument had been mostly stored on the spacecraft, under clean controlled atmospheric conditions. Microchannel plates were known to have a limited shelf life when exposed to the atmosphere and oxygen, which degrade MPCs. The SSJ5 SN16 sensor instrument response was measured and recorded as was the beam monitor detector count rates.

3.1.1 Calibration Using Electron Beam: SSJ5 SN16 with Old MCPs

- May 17, 2001, SSJ5 SN16 electron calibration; energy range 1400 – 1280 V
- May 18, 2001, SSJ5 SN16 electron calibration; energy range 650 – 590 V
- June 4, 2001, Mapping of electron beam accomplished

3.1.2 Calibration Using Ion Beam: SSJ5 SN16 with Old MCPs

- June 7, 2001, SSJ5 SN16 underwent a partial ion calibration, energy range 870 – 960 V
    - The ion calibration was aborted after observing the instrument was drawing too much current. It was decided to stop calibration and allow Amptek Inc. to proceed with the refurbishment in a stepwise fashion (see Section 1.1 for details).

3.1.3 Calibration Using Ion Beam: SSJ5 SN16 with Old MCPs & Refurbished Electronics

The electronics part of the refurbishment (transformer replacement) was accomplished by Amptex Inc. The sensor then continued calibration at the AFRL calibration facility at Hanscom AFB, MA.

- August 8, 2001, ion calibration; energy range 930 – 1020 V
- August 9, 2001, ion calibration; energy range 4240 – 4680 V

- August 14, 2001, ion calibration; energy range 930 – 1020 V range with lowered particle flux
- Removed outer screen covering apertures to enhance geometric factors
- August 20, 2001, ion calibration, energy range 890 – 1000 V range
- Enlarged electron and ion apertures to further enhance geometric factors
- August 24, 2001, ion calibration, 8 energy range 90 – 1000 V range

3.1.4 Calibration Using Ion Beam: SSJ5 SN16 with New MCP

New microchannel plates were installed and calibration continued.

- August 30, 2001, ion calibration, energy range 890 – 1000 V
- August 31, 2001, ion beam maps

3.1.5 Calibration Using Electron Beam: SSJ5 SN16 with New MCPs

- September 4, 2001, electron calibration, energy range 1400 – 1280 V
  - Data analysis: Observed cross-talk after MCP replacement.
- September 14 – 20, 2001, continued to operated sensor in chamber
  - Tried to encourage "clean-up" over time (full out-gassing of sensor).
  - Removed sensor from chamber and adjusted threshold resistors to match gain of new MCPs in order to address the cross-talk (see Section 1.2 for details).

3.2 Full Calibration of SSJ5 SN16 after Completing Refurbishment

3.2.1 Checkout Using Electron Beam

- October 25, 2001, energy range 1400 –1280 V
  - This electron calibration was performed to verify that the cross-talk was eliminated with the replacement MCPs and the addition of resistors.

3.2.2 Calibration Using Ion Beam

- October 29, 2001, energy range 890 – 1000 V
- October 30, 2001, energy range 4060 – 4500 V
- October 31, 2001, energy range 1895 – 2075 V
- November 1, 2001, energy range 8890 – 9605 V
- November 2, 2001 energy range 410 – 465 V
- November 5, 2001, energy range 186 – 215 V
- November 5-6, 2001, energy range 880 – 1000 V
  - Higher resolution and lower beam flux
- November 6, 2001, mapping of ion beam

3.2.3 Calibration Using Electron Beam

- November 9, 2001, energy range 650 – 590 V

- November 12, 2001, energy range 3010 – 2790 V
- November 12-13, 2001, energy range 297 –273 V
- November 13, 2001, energy range 6500 – 6050 V
- November 14, 2001, energy range 14100 – 13260 V
- November 15, 2001, mapping of electron beam

3.3 Recheck of Calibration after Final Environmental Testing

3.3.1 Final Environmental Testing

During the period November 14-20, 2001, the sensor was subjected to cleaning, staking, flight PROM installation and final electrical checks. On November 26, 2001, it went through an acceptance level vibration test. The period from 27-29 November, 2001, thermal vacuum testing was started, which was halted due to watchdog timer resets. In December 2001 – January 2002, the following was accomplished:

1. Identified broken lead in crystal oscillator caused by last vibration test.
2. Replaced crystal oscillator.
3. Resumed thermal vacuum testing, which were halted due to continued watchdog timer resets.
4. Replaced PROM when obscure problem with flight PROM due to use of new PROM burner was found.
5. Completed thermal vacuum cycles with no incident.
6. Put CPU board through final vibration test.
7. Completed one more thermal vacuum cycle.

3.3.2 Electron Calibration Check

Electron calibration check was made to ensure the calibration was unchanged after final flight PROM installation and environmental testing.

- February 8, 2002, energy range 1400 – 1280 V

3.3.3 Electron and Ion MCP Efficiency Study

The electron and ion MCP efficiency study consisted of an abbreviated set of scans that were comprised of 6 azimuths scans separated by 0.5 degrees, 2 elevations scans separated by 1 degree, each scan with 7 energies separated by 0.5 to 1% for each energy step (energy channels 2 - 19 or 20 keV to 30 eV; did not use Channel 1 or 30 keV). These abbreviated scans were used in conjunction with the full calibration runs to produce a final set of geometric factors for the instrument.

- February 14-15, 2002: Electron MCP efficiency study scans
- February 21, 2002, ion calibration check, energy range 860 – 970 V
  - Ion calibration check to ensure the calibration was unchanged after final flight PROM installation and environmental testing.
- February 22 and 25, 2002: Ion MCP efficiency study scans

- Same abbreviated set of scans as described above.

After completion of the MCP efficiency study, the SSJ5 SN16 was then taken to Amptek Inc. in Bedford MA for final electrical checks. The sensor was returned to AFRL on April 17, 2002 for storage at Hanscom AFB MA until June 27, 2002 when it was delivered to Northrop Grumman Baltimore, MD, from there it was transportation to Vandenberg AFB. Ultimately it was launched on October 18, 2003, on DMSP F16.

4. RESULTS AND DISCUSSION

Calibration work on SSJ5 SN16 was initiated in September 2001 after installation of new microchannel plates. Cross-talk between angular zones was discovered. The cause of the cross-talk was traced to the fact that the new microchannel plates had a higher gain that the original microchannel plates. The cross-talk was successfully eliminated by changing threshold resistors associated with each preamplifier to match the new microchannel plate gain. Full calibration for electrons and ions was completed by Mid-November, without incident.

4.1 Example of Angular Response As Seen In Calibration Data

As an example of the angular response for each zone delineated in Figure 1, a set of raw counts of the angular response for the SSJ SN16 collected during the electron calibration accomplished on October 25, 2001 are shown in Figure 4. The electron particle energy beam chosen was 1350 eV, one of 13 energies sampled that day in the 1280 – 1400 eV range. Recall that the field of view is a 4º by 90º fan for electrons and ions ranging from zenith to the horizon. The 90º field of view (or the zenith view) is divided into six 15º zones or sectors, as shown in Figure 1. Figure 4 shows the composite of all 6 zones of angular response calibration data given in raw counts, which have been interpolated by the plotting routine.

Figures 5 – 10 are contour plots of the angular response in raw counts recorded in each of the six zones during the electron calibration accomplished on October 25, 2001. The data presented in Figures 5 – 10 is the same as that shown in Figure 4. The dependence of elevation angle on azimuth angle can be clearly seen in the tilted appearance of zones 1, 2, 5, and 6 (Figures 5, 6, 9 and 10 respectively).

4.2 Effects of Changing Microchannel Plate

The geometric factors (g-factors) are shown in Figures 11 and 12 as a function of zone, which were obtained during different calibration runs made over a period of about 8 years. Figure 11 corresponds to geometric factors for 1.3 keV electrons, and Figure 12 to the 1 keV ions in each zone. In Figure 11, the data taken in 1993 and May 2001, the SSJ5 SN 16 still had its original MCPs whereas the data taken in October 2001 and February 2002 it had the new MCPs installed. The 1993 and May 2001 geometric factors were adjusted for the new aperture sizes and screen removal that was performed in August 2001 (see Section 1.1). However, it is worth noting that

the 1993 calibration work was only intended to demonstrate instrument integrity and verify the design and manufacturing process but has been included here for completeness.

In Figure 11, there was some uncertainty in differences between experimental setup between the data taken in 1993 and 2001. Also, some earlier data processing assumptions may have affected the shape of geometric-factor curve calculated from the 1993 data as compared to the 2001 and 2002 for both the electron and ion geometric factors. Similarly as for the electron geometric factors, the SSJ5 SN16 ion geometric factors had the original MPCs for the data taken in 1993 and August 2001, whereas the MCPs were replace prior to the October 2001 and February 2002 data acquisition. The 1993 ion geometric factors were also corrected for new aperture size and screen removal performed in August 2001.

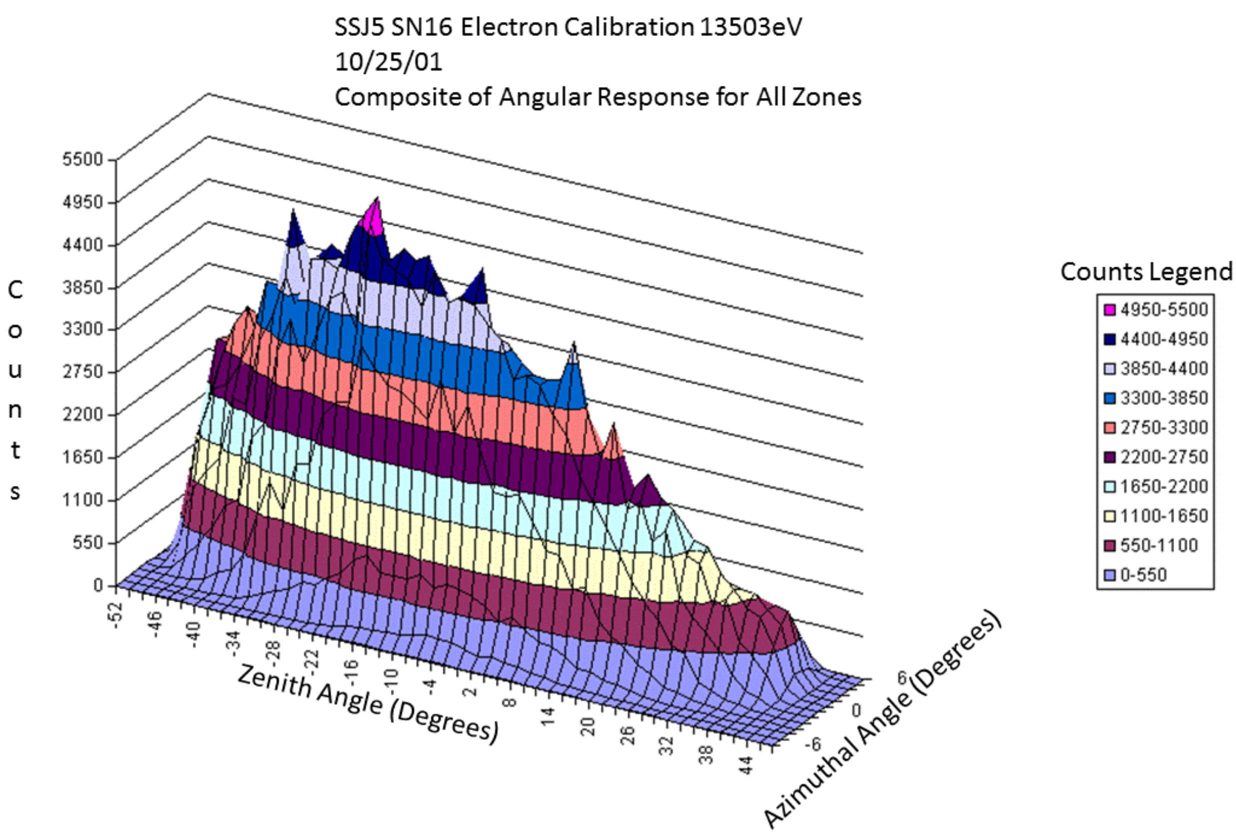

Figure 4. SSJ5 SN16 zonal angular response to 1350 eV electrons measured on 10/25/01

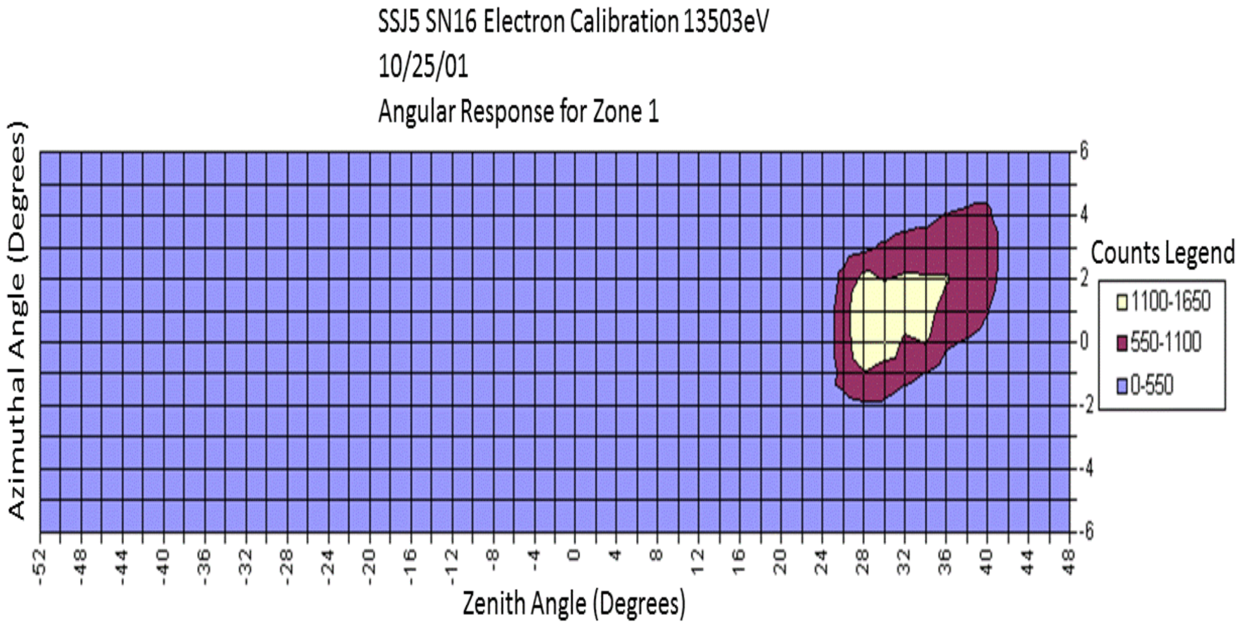

Figure 5. SSJ5 SN16 zone 1 angular response to 1350 eV electrons measured on 10/25/01

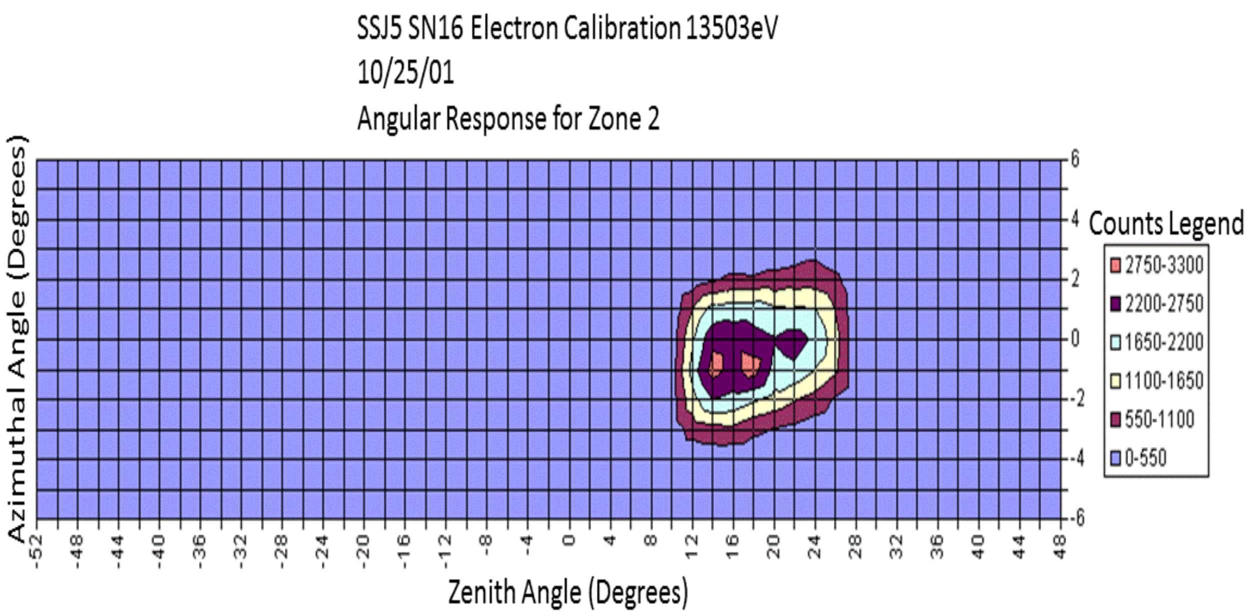

Figure 6. SSJ5 SN16 zone 2 angular response to 1350 eV electrons measured on 10/25/01

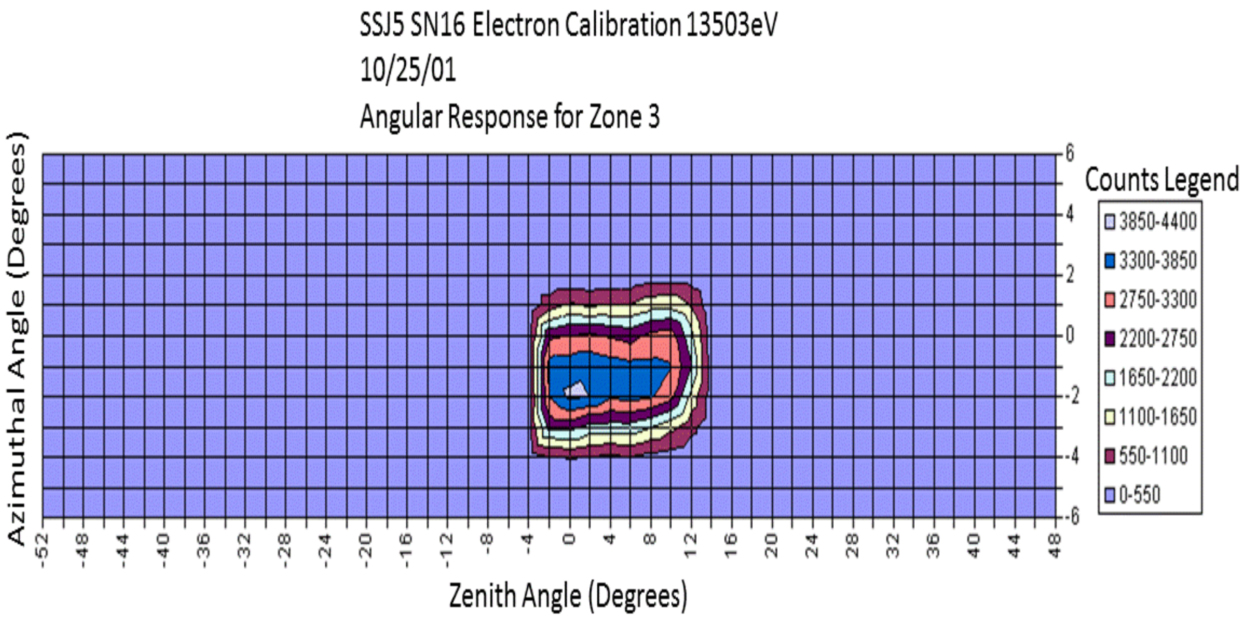

Figure 7. SSJ5 SN16 zone 3 angular response to 1350 eV electrons measured on 10/25/01

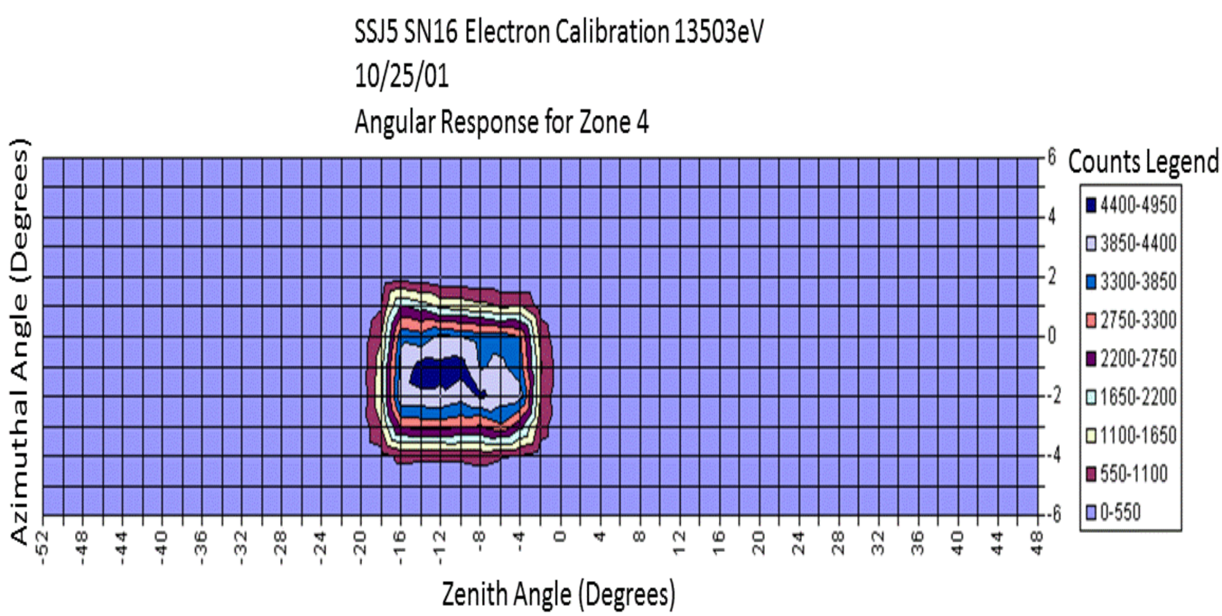

Figure 8. SSJ5 SN16 zone 4 angular response to 1350 eV electrons measured on 10/25/01

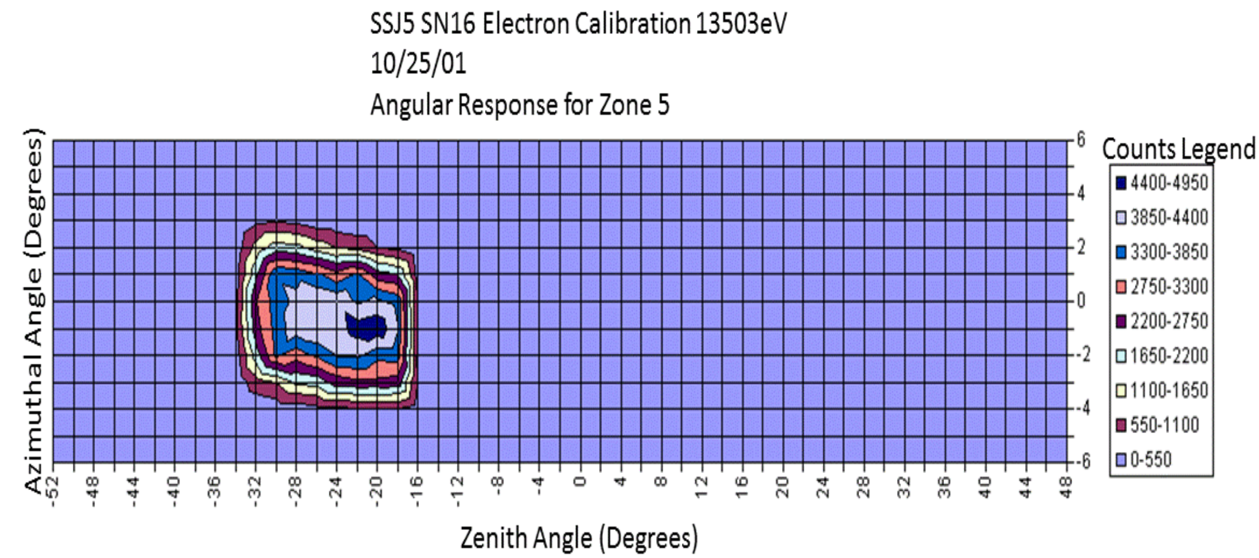

Figure 9. SSJ5 SN16 zone 5 angular response to 1350 eV electrons measured on 10/25/01

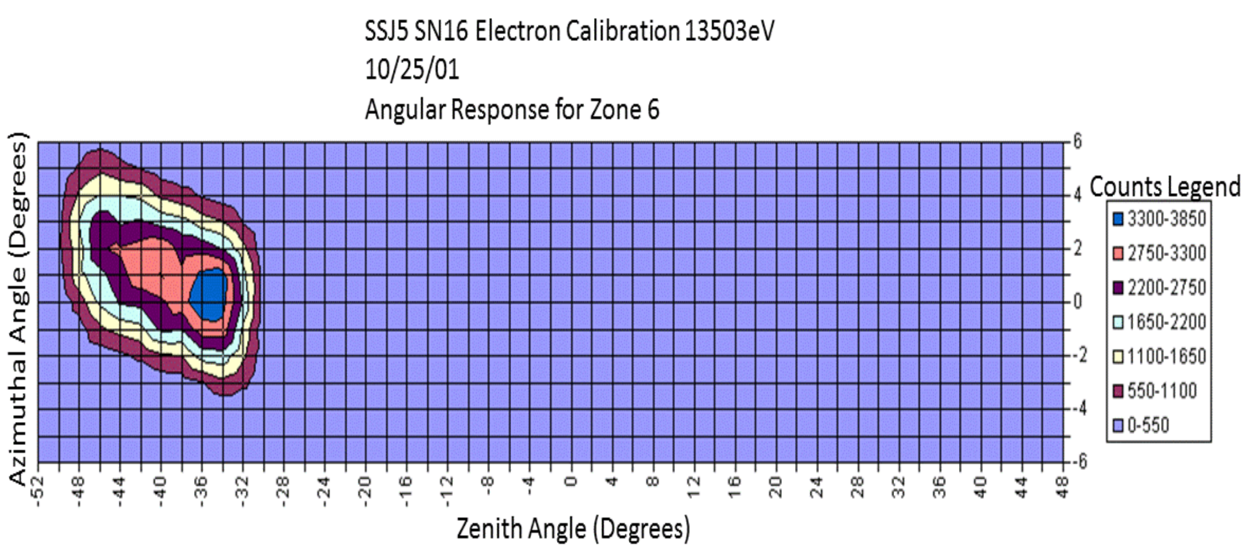

Figure 10. SSJ5 SN16 zone 1 angular response to 1350 eV electrons measured on 10/25/01

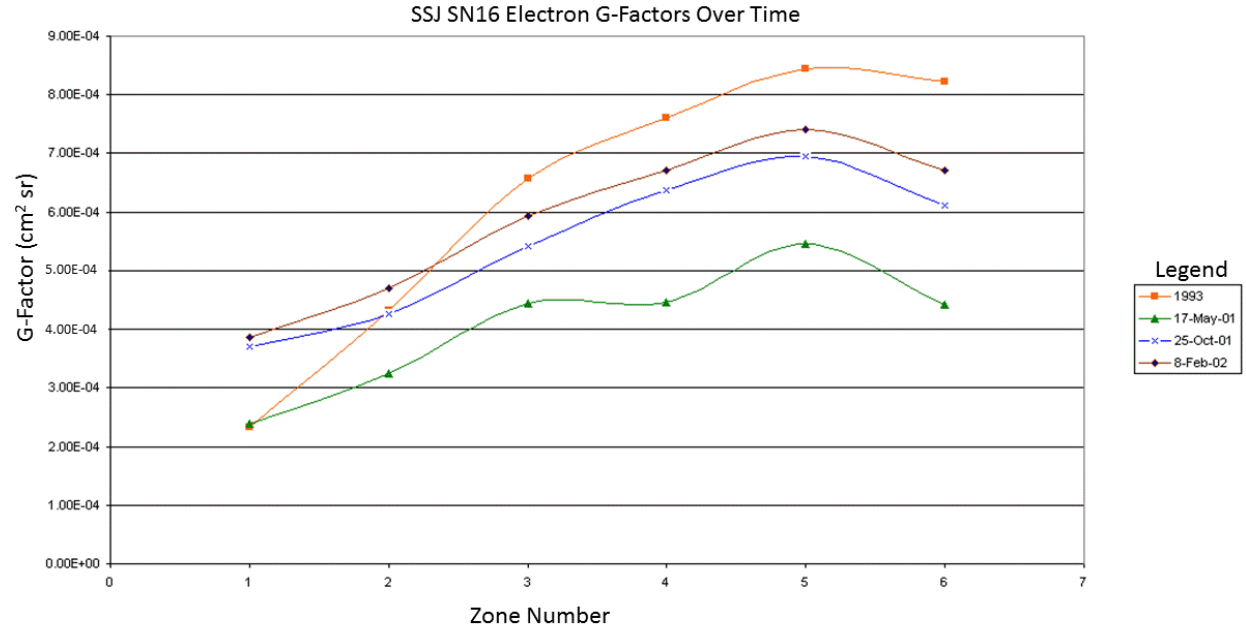

Figure 11. SSJ SN16 geometric factors for 1 keV electrons for each zone as calculated from measurements taken over a period of about 8 years

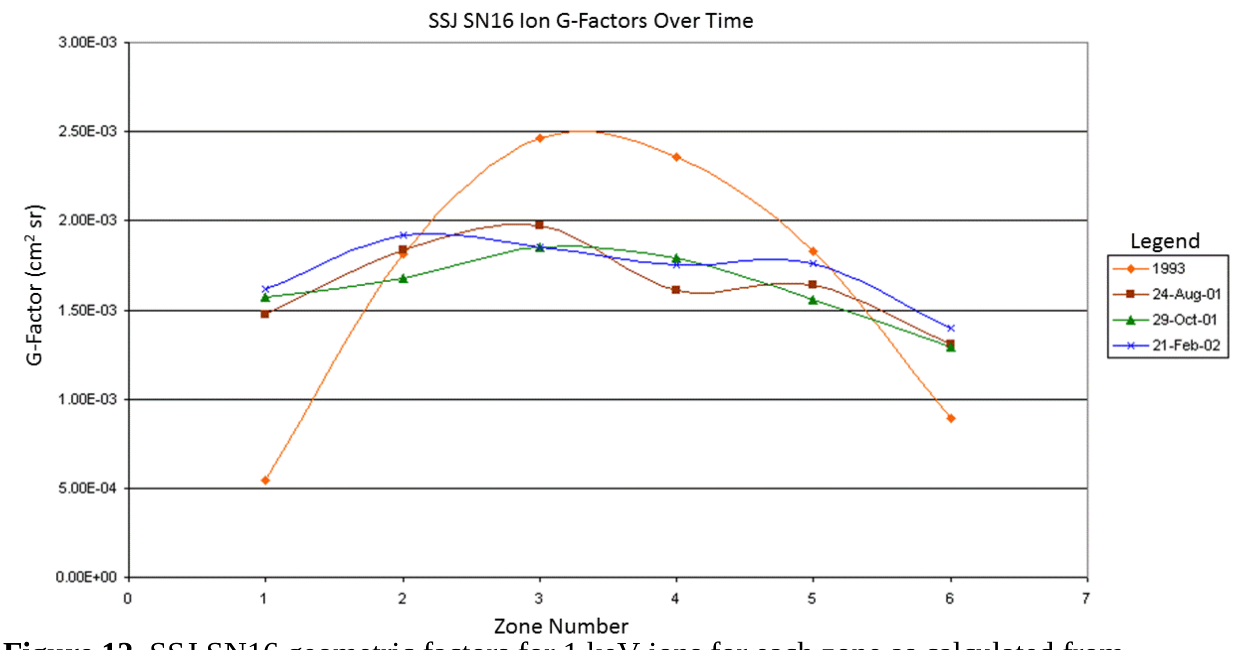

Figure 12. SSJ SN16 geometric factors for 1 keV ions for each zone as calculated from measurements taken over a period of about 8 years

4.3 Performance Improvement with Elimination of Zonal Cross-talk

With the installation of new MCPs, the cross-talk between angular zones was discovered. The new MPSs had a higher gain than that of the original MCPs, which was determined to be the cause of the cross-talk. The effect of near eliminating cross-talk between the zones by changing

the threshold transistors in the SSJ5 SN16 can be clearly seen in the geometric factors calculated from electron data (1 keV) shown in Figures 13 and 14. Also shown in Figure 13 are the geometric factors calculated from data that was corrected for the substantial background created from the contributions of counts from adjacent zones, i.e. cross-talk. The contribution to the geometric factors from the cross-talk background from the adjacent zones is shown and its percentage to the geometric factor calculation. Figure 13 shows geometric factors calculated from data acquired with SSJ5 SN16 after the MCP was replace. It is evident from Figure 13 that there was a marked improvement in the geometric factors with the cross-talk substantially reduced. With the changing of the threshold transistors the cross-talk for the electron measurements were reduce from between 3 – 5% down to less than 0.1%.

Figures 15 and 16 show the same effect however for the geometric factors calculated from the ion measurements (1 keV). The cross-talk for the ion measurements were almost total suppressed with the addition of the new threshold transistors as can be seen in figures 15 and 16.

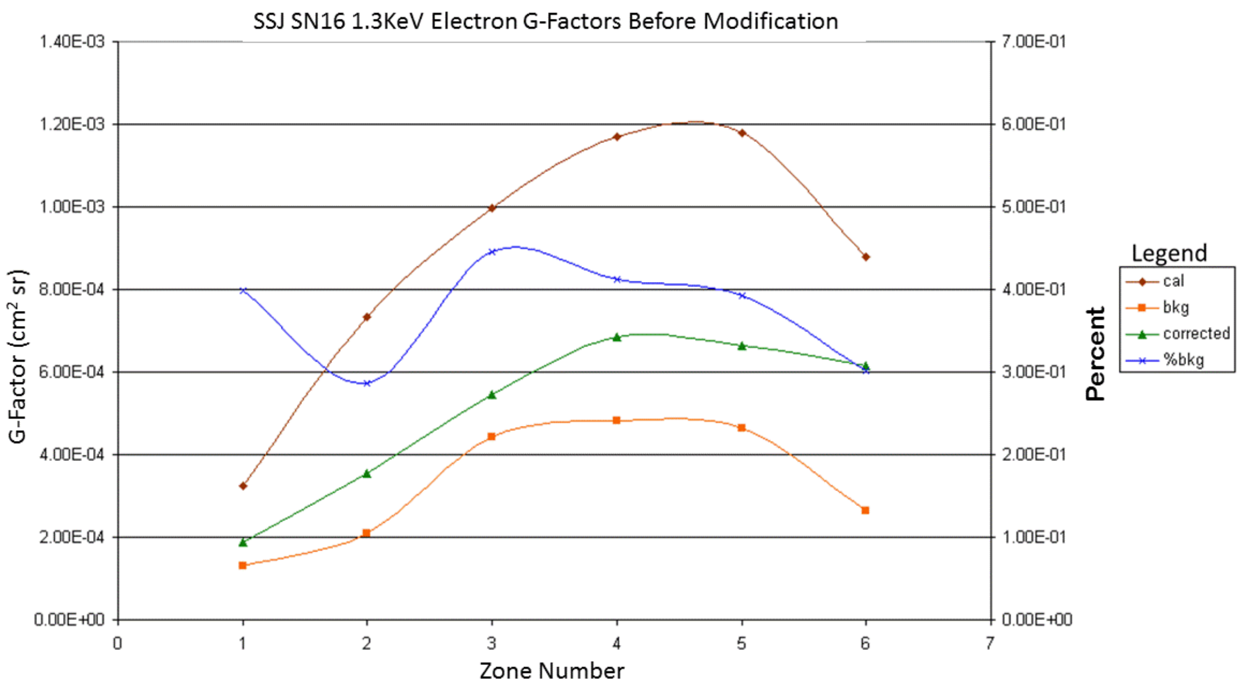

Figure 13. SSJ5 SN16 1.3 keV electron geometric factors after correcting for cross-talk caused by installation of new MCP, where calibration data was corrected for substantial background from adjacent zones

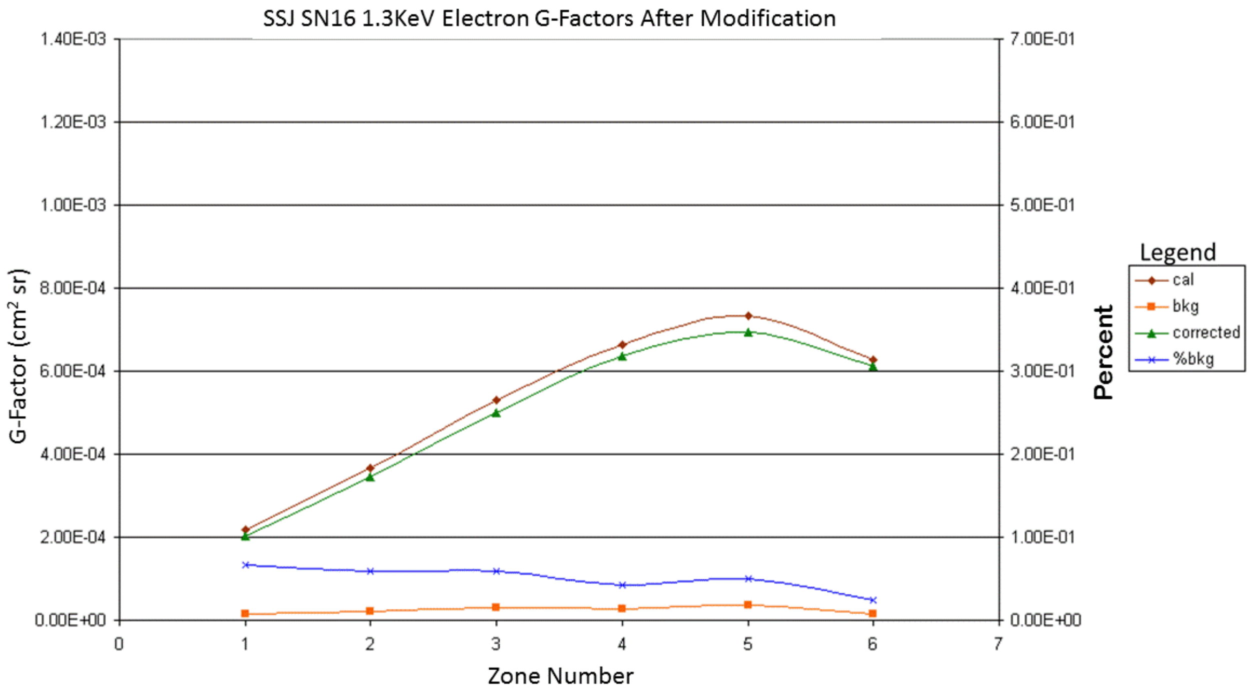

Figure 14. SSJ5 SN16 1.3 keV electron geometric factors after correcting for cross-talk with new MCP and changing the threshold transistors, where calibration data was corrected for minimal background from adjacent zones

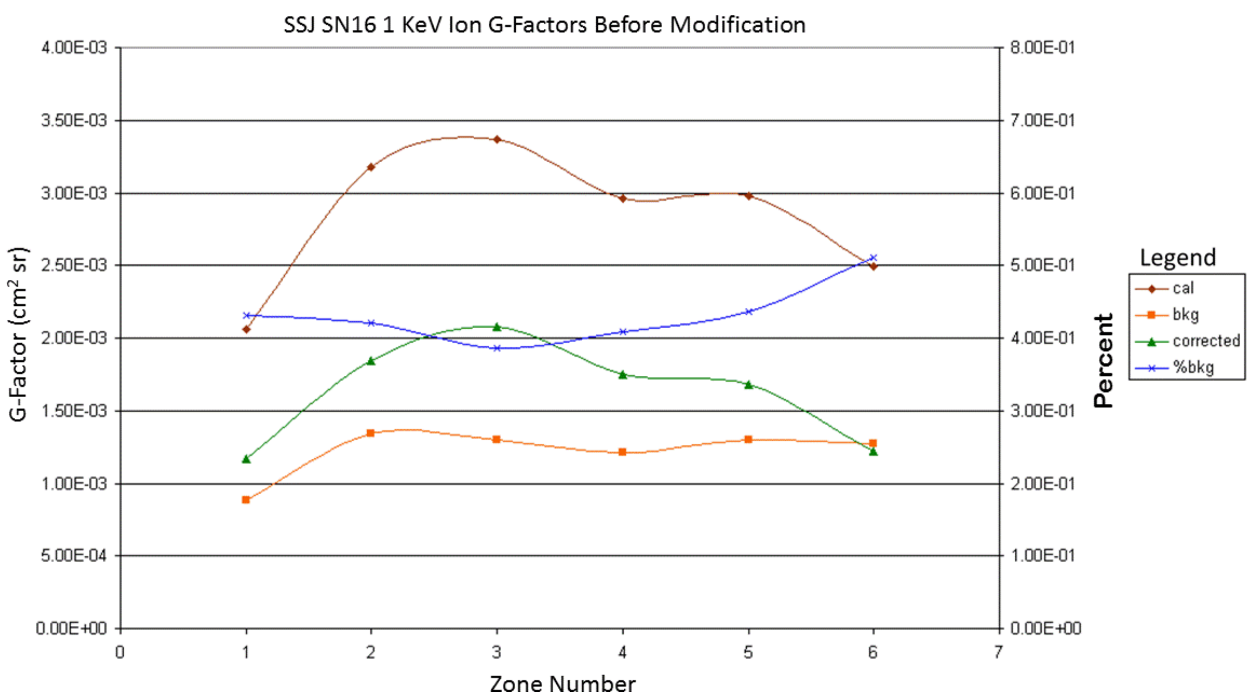

Figure 15. SSJ5 SN16's 1 keV ion geometric factors after correcting for cross-talk caused by installation of new MCP, where calibration data was corrected for substantial background from adjacent zones

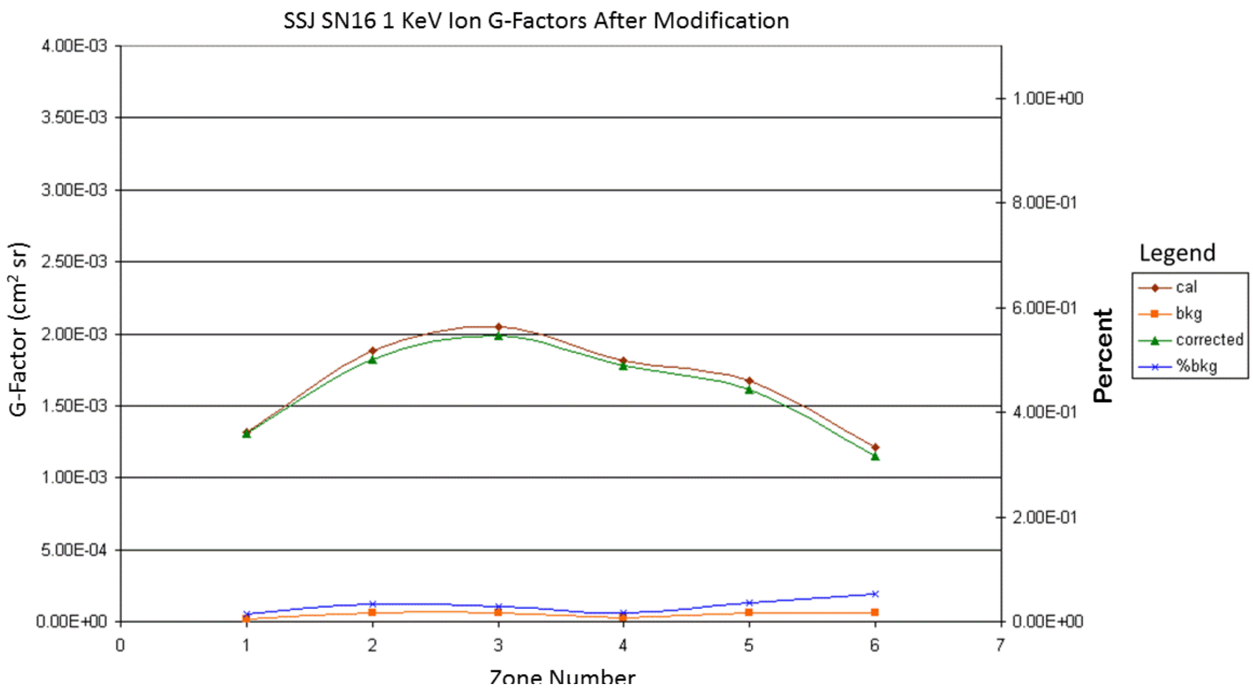

Figure 16. SSJ5 SN16's 1 keV ion geometric factors after correcting for cross-talk with new MCP and changing the threshold transistors, where calibration data was corrected for minimal background from adjacent zones

4.4 Geometric Factors Determination

The goals of the SSJ5 SN16 calibration was to determine, as accurately as possible, Mode A energy independent geometric factors, the zone profiles, and the MCP efficiency. The peak geometric factors are energy independent. Also, the peak geometric factors are essentially a product of Mode A's energy dependent geometric factor and the MCP efficiency. The geometric factor for Mode A is the product of the peak geometric factor and ΔE, the width of the energy channel. $\Delta E/E$ is a constant that was determined experimentally to be 4% for the SSJ5 SN16.

4.4.1 Mode A Geometric Factors

The calibration of SSJ5 SN16 consisted of scans for six of the nineteen energy channels over all angles (zenith and azimuthal). Also conducted were 'mini-scans' for eighteen (all but the highest energy) channels for each of the six zones. This was done for both electrons and ions. The result of an energy-angle scan was a four dimensional array of count rates vs. azimuth angle, elevation angle, and energy for each of the six directional zones. Geometric factors for each energy and zone were calculated by doing a numerical integration over the two angular dimensions and dividing by the electron or ion beam flux. By definition the Mode A peak geometric factors are the peak values of the sum of the six zone geometric factors for a given energy, an example is shown in Figure 17.

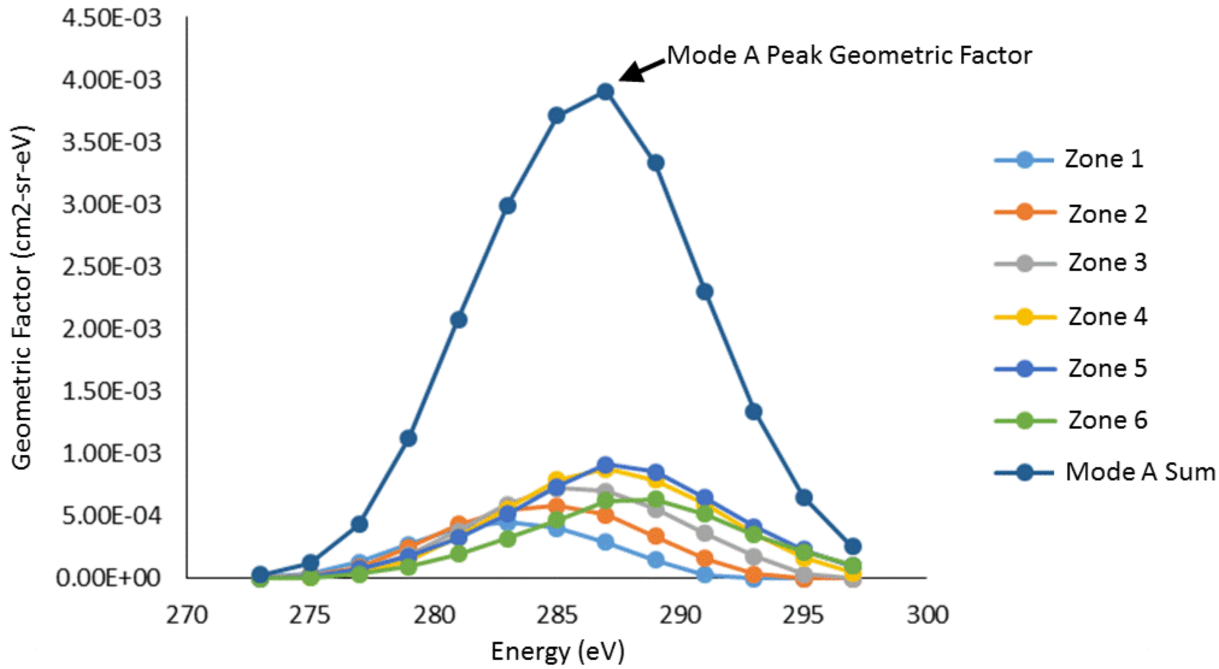

Figure 17. Zone and Mode A geometric factors calculated from electron calibration data (prior to adjustments) taken on November 12, 2001, where Mode A geometric factors are the sum of all six zone geometric factors

The peak geometric factor for a SSJ5 is the largest geometric factor as function of channel number (i.e. energy) in a given zone and it also accounts for MCP current efficiency. If the SSJ5 SN16 was a perfect sensor that behaved according to the theoretical model discussed in Section 2.2 and where the MCPs were 100% efficient at all energies, there would be a constant peak geometric factor for the four by fifteen degree central zones (see Figure 1). Also as discussed in section 2.2 bullet 9, there is a cosine area reduction factor, which for the SSJ5 SN16 is 0.79 for the two edge zones, 1 and 6, and 0.92 for the intermediate zones, 2 and 5 (see Figure 1). Thus for Mode A, the theoretical peak geometric factors, with the cosine reduction included, are 1.08×10^{-1} cm^2-sr for ions and 4.57×10^{-3} cm^2-sr for electrons (six times the individual zone geometric factor and reduced by 0.9 for the average cosine area factor). Since a SSJ5 is not quite perfect and a small unknown imperfection in the electron sensor resulted in the peak geometric factors from zone 1 and 6 differing by a factor of two when they should have been identical, see Figure 18. Similarly Figure 19 shows the ion sensor peak geometric factor profiles differ as well but not to the extent of the electron peak geometric factors.

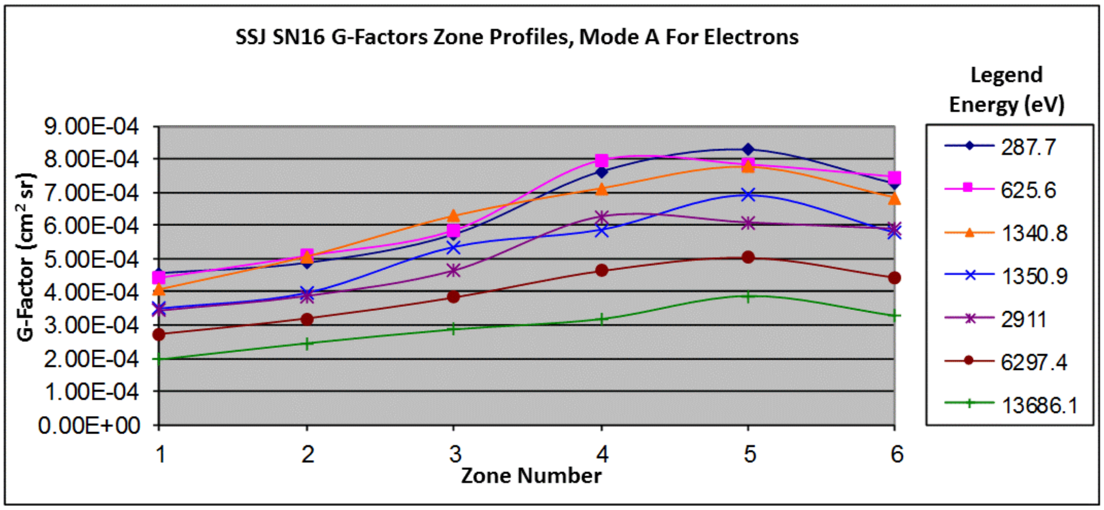

Figure 18. Electron Mode A peak geometric factors for various energies SSJ5 SN16

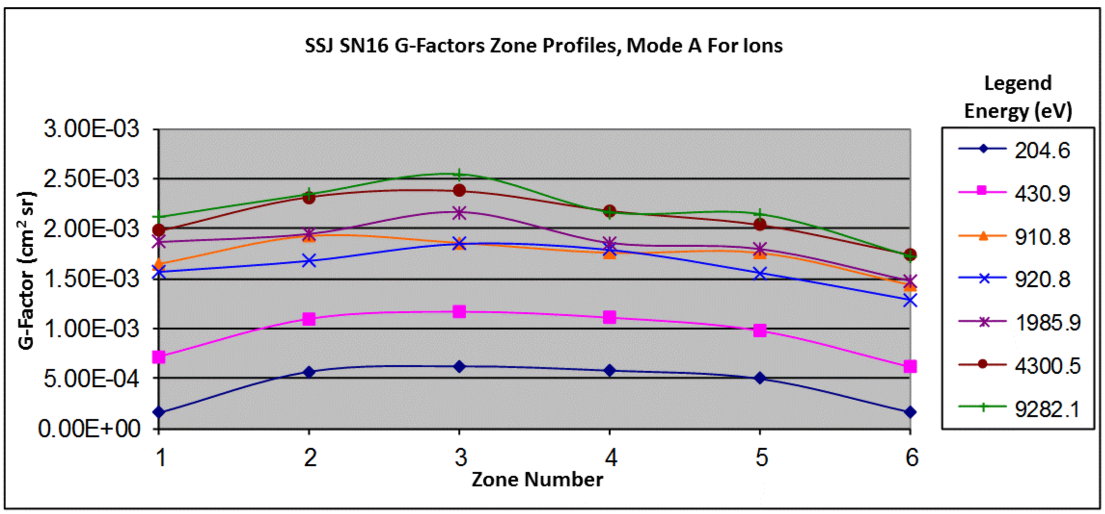

Figure 19. Ion Mode A peak geometric factors for various energies SSJ5 SN16

In Table 4, the Mode A peak geometric factors (cm^2-sr-eV) and the geometric factors (cm^2-sr) are given. The peak geometric factors include the MCP efficiency, which we assume to be 100% at the energy corresponding to the peak observed. The Mode A geometric factors (cm^2-sr) in Table 1 is the product of the peak geometric factor for a given energy (or channel number) and measured channel energy width, $\Delta\mathcal{E}$, where $\Delta\mathcal{E}/E$ was determined experimentally to be 4%. Figures 20 and 21 are plots of the electron and ion peak geometric factors, respectively, given in Table 4.

Table 4. Mode A 19 energy channel's geometric factors for electrons and ions

Channel Number, i	Channel Center Energy, E(eV)	Channel Energy Width, $\Delta\mathcal{E}$(eV)	Electron Peak Geometric Factor (cm^2-sr)	Electron Geometric Factor (cm^2-sr-eV)	Ion Peak Geometric Factor (cm^2-sr)	Ion Geometric Factor (cm^2-sr-eV)
1	30000	1200.384	0.00104	1.2520	0.01418	17.02000
2	20439	817.541	0.00128	1.0440	0.01359	11.11000
3	13925	556.907	0.00151	0.8426	0.01300	7.24100
4	9487	379.555	0.00175	0.6646	0.01239	4.70300
5	6463	258.550	0.00200	0.5171	0.01193	3.08400
6	4403	176.157	0.00225	0.3960	0.01104	1.94400
7	3000	120.024	0.00254	0.3045	0.01029	1.23500
8	2044	81.740	0.00278	0.2274	0.00966	0.78970
9	1392	55.714	0.00302	0.1682	0.00930	0.51810
10	949	37.938	0.00331	0.1255	0.00947	0.35930
11	646	25.853	0.00360	0.0931	0.00988	0.25540
12	440	17.612	0.00369	0.0651	0.00969	0.17070
13	300	12.001	0.00371	0.0445	0.00999	0.11980
14	204	8.175	0.00375	0.0307	0.01009	0.08248
15	139	5.570	0.00363	0.0202	0.00892	0.04968
16	95	3.795	0.00331	0.0126	0.00753	0.02858
17	65	2.586	0.00301	0.0078	0.00663	0.01714
18	44	1.761	0.00257	0.0045	0.00577	0.01016
19	30	1.200	0.00191	0.0023	0.00460	0.00552

.

4.4.2 Mode B Geometric Factor Determination

In Mode B, particle counts from the six angular sectors are acquired one zone at a time providing enhanced pitch-angle resolution. Also in Mode B, the particle counts for each zone are summed over the previous six seconds, where the six zones are not sampled simultaneously. However, the six-second resolution of mode B is less than the inherent one-second resolution of the SSJ5's Mode A. Both of these limitations of mode B are a result of the spacecraft restrictive telemetry allocation for the SSJ5s. The SSJ5 has been run for extended time periods in both Modes producing data from both mode A and B. While Mode B has reduced precision, it is useful for characterizing the degree of anisotropy of the particle fluxes and is used during on-orbit checkout.

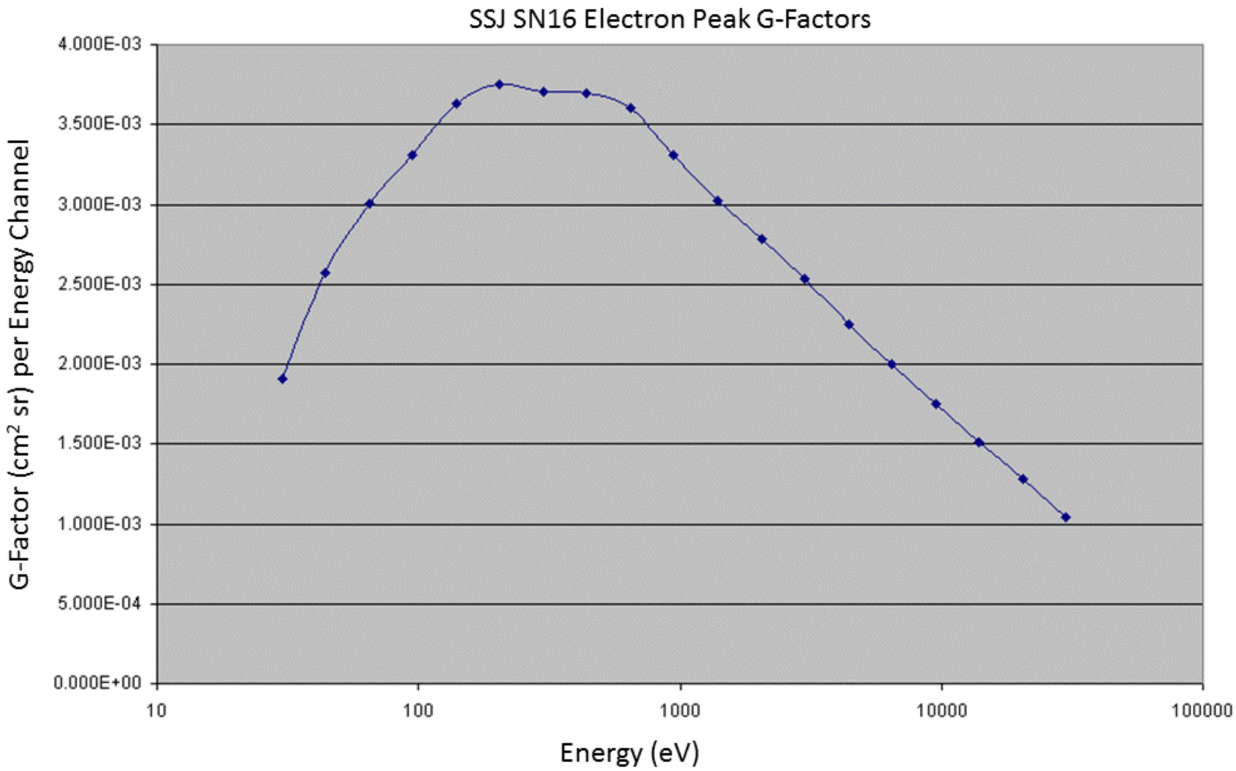

Figure 20. Mode A electron peak geometric factors from Table 4

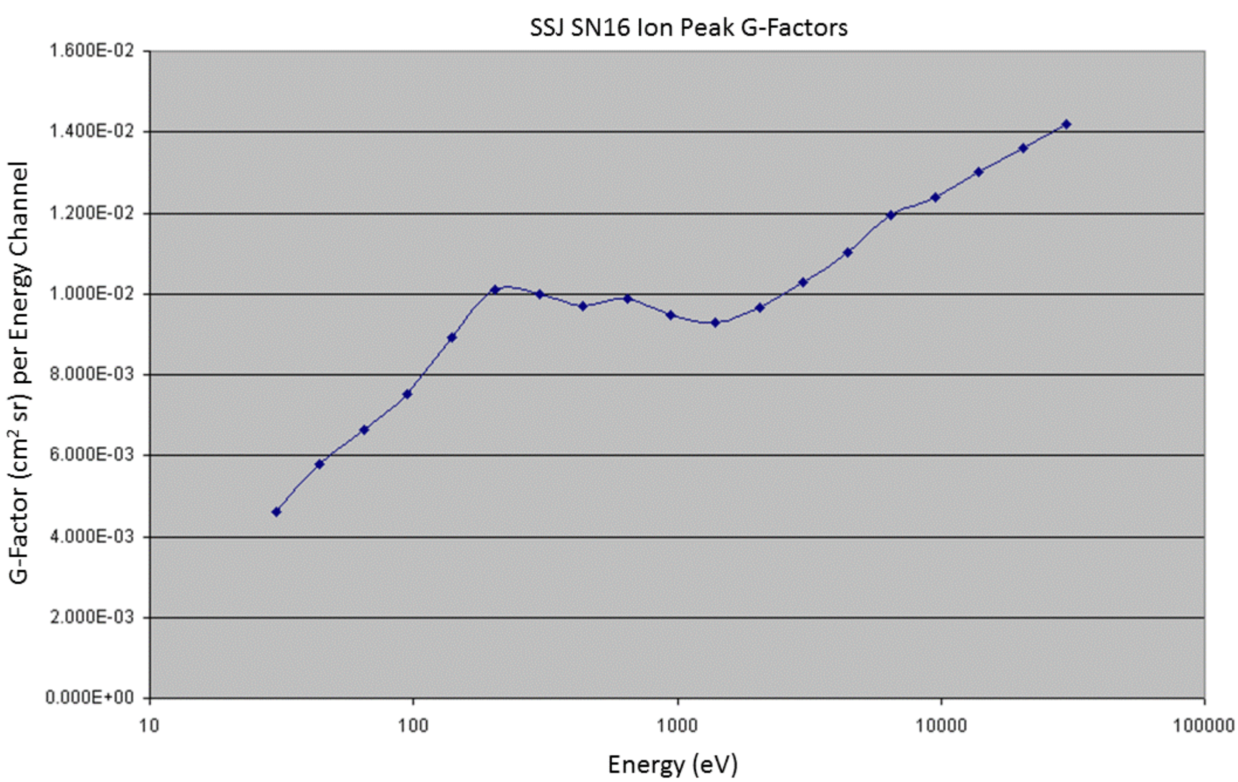

Figure 21. Mode A ion peak geometric factors from Table 4

The Mode B geometric factors can be generated by multiplying the Mode A geometric factors (last two rows found in Table 4) by the zone profile factor and dividing by six. The zone profile factors are the average of the zone peak geometric factors from the six full angle-energy scans, scaled so the inverse of the inverse sum up over the six zones equals six (Table 5). It is worth noting that the calculation of the flux (Equation 1), for Mode B operation, the particle accumulation time interval Δt is 300 ms rather than the 50 ms as used in Mode A.

Table 5. Computation of zone profile factors used for Mode B

Zone geometric factor corrections							
	z1	**z2**	**z3**	**z4**	**z5**	**z6**	sum
electrons	0.739	0.854	1.036	1.278	1.372	1.227	6.506
ions	1.011	1.194	1.265	1.149	1.083	0.849	6.551
electrons	1.35318	1.17096	0.96525097	0.7824726	0.728863	0.8149959	5.815723
ions	0.98912	0.837521	0.79051383	0.870322	0.923361	1.1778563	5.588694
electrons	1.396057	1.208063	0.99583597	0.8072661	0.751958	0.8408199	6
ions	1.061915	0.899159	0.84869259	0.9343743	0.991317	1.264542	6
scaled such that summation of inverses = 6							
electrons	0.716303	0.827771	1.00418144	1.2387489	1.329862	1.1893153	6.306182
ions	0.941695	1.11215	1.17828295	1.0702349	1.008759	0.7908002	6.101922

4.4.3 Microchannel Plate Efficiency Factors

The MCP efficiency factors are determined by the mini-scans. The most accurate way to measure the MCP efficiency profile is to do a search (in energy and both angles) for the peak counting rate at each SSJ5 energy step for one of the central zones. This was a simple measurement, and all 18 steps can be done during a single session where it was possible to keep all relevant experimental conditions fixed. The curves were then normalized to one for the electron peak (204 eV electrons), and assigned to the 13 keV channel for ions where there was no clear peak in the efficiency curve. Electron and ion beam spreading effects and energy structure have also been accounted for low energies. Below about 100 eV, the electron beam was not totally unidirectional. Below about 500 eV the ion beam exhibits a non mono-energetic structure that can be modified experimentally. This structure has been characterized and compensated for in the MCP efficiency calculation.

The MCPs efficiency is not constant across the energy range for electrons and ion detection. The MCP efficiency drops off rapidly for low energy electrons and less rapidly for higher energy electrons with a peak (assumed to be 100%) around 500 eV, as shown in Figure 22. The MCP efficiency for ions also drops off at low energy and was expected to plateau or fall off gradually with energy starting somewhere above 1000 eV shown in Figure 23. Our measurements indicate

that our MCPs had a peak efficiency just above 300 eV (200 eV particles and 100 eV post-acceleration) for electrons (see Figure 22) and above 20 keV for ions (see Figure 23).

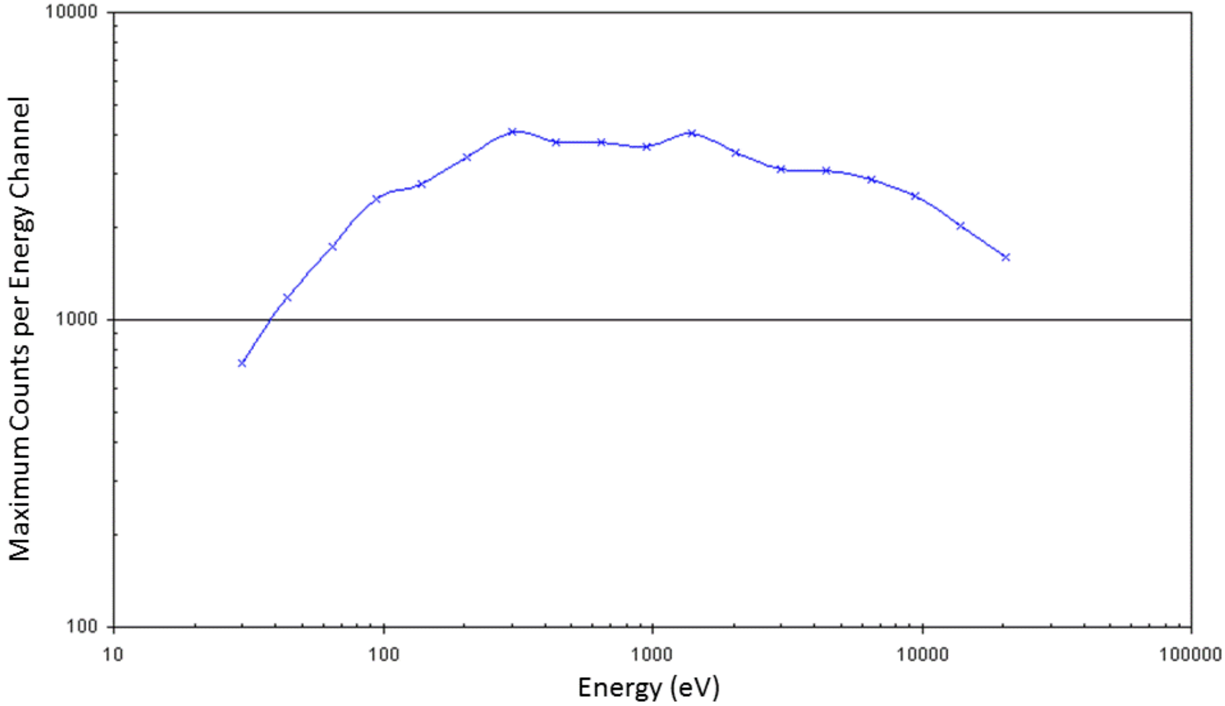

Figure 22. Microchannel plates efficiency for electron detection as function of energy

5. CONCLUSION

Calibration work on SSJ5 SN16 was initiated in September 2001 after installation of new microchannel plates. During the refurbishment, two modifications were made to the sensor in order to improved particle counting statistics: the electron and ion aperture sizes were increased and the outer screen covering the apertures was permanently removed. These modifications have been made to all SSJ5s during refurbishment. Cross-talk between angular zones was discovered. The cause of the cross-talk was traced to the fact that the new microchannel plates had a higher gain that the original microchannel plates. The cross-talk was successfully eliminated by changing threshold resistors, associated with each preamplifier, to match the new microchannel plate gain. Full calibration for electrons and ions was completed by Mid-November 2001, without incident.

After repair, refurbishment, calibration, testing (electrical, random vibration, thermal vacuum tests), and recalibration, the SSJ5 SN16 sensor was considered to be flight worthy. Geometric factors for Mode A and ΔE/E values were measured during the calibration process and are compare to the model values in Table 6. The model values for geometric factors for ions and electrons are based on the simple model presented in Section 2.2 with the results reported in Section 2.3.

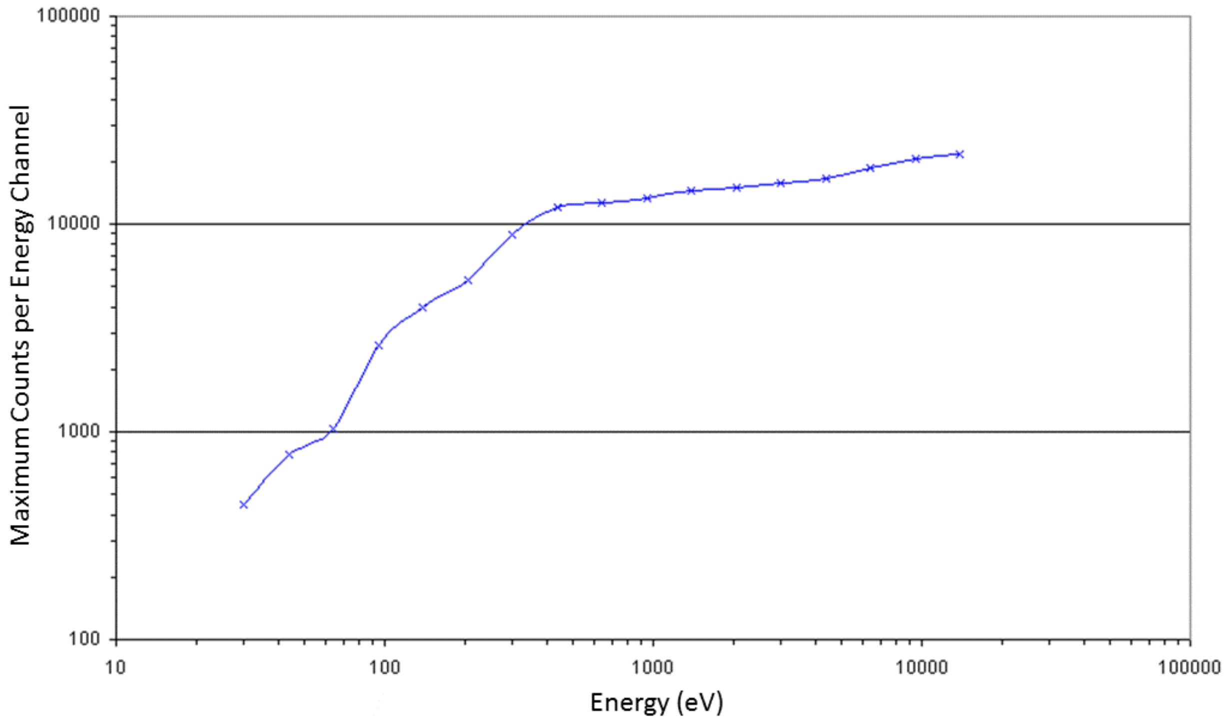

Figure 23. Microchannel plates efficiency for ion detection as function of energy

Single sector the energy dependent geometric factor, GF(E), values have been multiplied by 6 (for the 6 zones), and by 0.9 (average cosine factor) as described in Section 4.4.1. Note that the theoretical model makes simple assumptions. Moreover, all SSJ5 have slight manufacturing imperfections such as inhomogeneity in the sphere forms or non-concentricity when mounted in the SSJ5.

Table 6. Measured compared to model values of geometric factors and ΔE/E

	Model Values	Calibration Values
GF(E) ions (Mode A)	$1.08\text{x}10^{-2}$ cm^2-sr	$1.30\text{x}10^{-2}$ cm^2-sr
GF(E) electrons (Mode A)	$4.57\text{x}10^{-3}$ cm2-sr	$3.75\text{x}10^{-3}$ cm2-sr
ΔE/E	5.4%	4%

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

α	Focused Angle
$\Delta\mathcal{E}$	Measured channel energy width
ΔE	Channel energy spacing for calculating the integrated energy flux, JE
AFB	Air Force Base
AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
A_p	Aperture diameter
C_i	Number of particle counts measured
cm	Centimeter
CPU	Central Processing Unit
CRRES	Combined Release and Radiation Effects Satellite
DC	Direct Current
DMSP	Defense Meteorological Satellite Program
E	Energy
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EST	Equipment Status Telemetry
eV	Electron Volt
F16	Flight 16
FWHM	Full Width Half Maximum
GF	Geometric factor
g-factor	Geometric factor
GSE	Ground Support Equipment
i	Channel number
J	Integrated number flux
J_i	Differential number flux
JE	Integrated energy flux
JE_i	Differential energy flux
k	Analyzer Constant
keV	Kilogram electron Volt

kg	Kilogram
km	Kilometers
m	Meter
mA	milliampere
MA	Massachusetts
MCP	Microchannel plate
MD	Maryland
MMAS	Martin Marietta Astro Space
msec	Millisecond
N_2	Molecular Nitrogen
nm	Nanometer
OAR	Open Area Ratio
OLS	Operational Linescan System
PROM	Programmable Read-Only Memory
R_i	Inner Radius
R_o	Outer Radius
RV	Space Vehicles Directorate
s	Second
S20	DMSP Spacecraft Number 20
sr	Steradian
SSJ5	Special Sensor J5
SSJ4	Special Sensor J4
SN	Serial Number
SPREE	Shuttle Potential and Return Electron Experiment
t	Time
TSS-1	Tethered Satellite System
TR	Technical Report
V	Volt
W	Watt

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